

## Measurement of the ratio double/single muon events as a function of rock depth with MACRO

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**Abstract.** We report the measurement by the MACRO experiment of the ratio of double muon events over single muon events as a function of rock depth. Particular attention has been devoted to the analysis of high zenith angle events. Results are compared to the expectation of a detailed simulation performed with HEMAS-DPM Monte Carlo. No deviations with respect to “standard physics” predictions have been found.

### 1 Introduction

In deep underground experiments, the ratio  $N_2/N_1$  of double muon events over single muon events is expected to decrease as a function of the rock depth, unless some exotic phenomena occur. The ratio  $N_2/N_1$  has been studied in several underground experiments and phenomenological papers (Elbert, 1981).

In general, it is hard to conclude that these measurements are in contrast with ‘standard physics’ expectations, because the cuts required to cancel the contribution of muon pair production and of fake tracks due to hadro-production are not applied to data. Moreover, a comparison with Monte Carlo expectations is not reported in these papers.

Much stronger conclusions arise from a recent measurement of the LVD collaboration at Gran Sasso. They have presented results on the ratio of multiple-muon flux to all-muon flux as a function of the rock depth (Ryazhskaya, 2000). They find that this ratio decreases for rock depth  $3000 < h < 7000 \text{ hg/cm}^2$  but increases for  $h > 7000 \text{ hg/cm}^2$ . The increase at large depth is in disagreement with the calculations performed with the CORSIKA (Capdevielle, 1992) and MUSIC (Antonioli, 1997) Monte Carlos (based on “standard physics”). In order to rule out the muon pair production as a possible mechanism generating the excess of multiple muon events, they required a minimum distance of 1 meter between the muons in the bundle. Their result cannot be explained

unless some other exotic phenomenon occurs with relatively high probability.

Here we report the results of a similar measurement performed with the MACRO detector at Gran Sasso. Our goal is to understand the prediction of standard physics in MACRO and to compare it with experimental data. This paper has a remarkable interest for MACRO, because it is the first analysis including multiple muon events at large zenith angle. We measured the ratio  $N_2/N_1$  of double muon events over single muon events as a function of the rock depth.

We did not include events with multiplicity  $> 2$  in the analysis for simplicity, since they represent a small fraction of the whole multiple muon sample: in the LVD experiment located near ours, only about 30 % of multiple muon events for  $h > 8000 \text{ hg/cm}^2$  have multiplicity  $> 2$ .

Rock depth is provided by the Gran Sasso map function  $h(\theta, \phi)$ . For each event, we had to determine the muon multiplicity  $N_\mu$  ( $N_\mu=1, N_\mu=2, N_\mu>2$ ) and the direction  $(\theta, \phi)$ .

The MACRO track reconstruction algorithm provides the number of tracks  $N_{HW}$ ,  $N_{HS}$  and  $N_{VW}$ , in three independent views, respectively: Horizontal Wires (HW), Horizontal Strips (HS) and Vertical Wires (VW).

One track is fitted in the HW view, when at least 4 aligned hits are found. In order to determine the selection cut, we used full Monte Carlo simulation (see next section) to generate all possible different event categories, according to reconstructed multiplicities  $N_{HW}$ ,  $N_{HS}$ ,  $N_{VW}$  (see Table 1). The event direction can be determined only for events with at least one track in two independent views. For that reason, samples 5 and 6 in the Table will not be considered in the analysis.

However, since we found that Sample 3 with  $N_{HW} = 0$ ,  $N_{HS} = 0$  and  $N_{VW} \geq 1$  contains a relevant number of events at large rock depths, we decided to recover these events performing a track fit in the Horizontal Wire view when there are 3 aligned hits.

Samples 4 and 7 were neglected because they represent a negligible fraction of the total data sample at all rock depths. Moreover, Sample 7 contains mainly mis-reconstructed events,

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Sample	$N_{HW}$	$N_{HS}$	$N_{VW}$	$h < 7000 \text{ hg/cm}^2$		$h > 7000 \text{ hg/cm}^2$	
				Events	%	Events	%
1	$\geq 1$	$\geq 1$	$\geq 1$	4,090,000	42.6	20,140	57.3
2	$\geq 1$	$\geq 1$	0	4,878,000	50.8	8,096	23.1
3	0	0	$\geq 1$	484,500	5.0	6,342	18.1
4	$\geq 1$	0	$\geq 1$	69,000	0.7	103	0.3
5	$\geq 1$	0	0	29,870	0.3	44	0.1
6	0	$\geq 1$	0	18,140	0.2	123	0.3
7	0	$\geq 1$	$\geq 1$	38,400	0.4	296	0.8
Total				9,607,910	100	35,144	100

**Table 1.** Monte Carlo samples classified according to the number of tracks reconstructed in Horizontal Wires ( $N_{HW}$ ), Horizontal Strips ( $N_{HS}$ ) and Vertical Wires ( $N_{VW}$ ) views. We report the total number and the percentage of events for two ranges of reconstructed rock.

where the number of tracks in HW view is smaller than the number of tracks in HS view. This is in contradiction with the observation that wires are more efficient than strips.

## 2 Monte Carlo simulation

Monte Carlo simulation is required to understand the prediction of standard physics for  $N_2/N_1$  in MACRO. The Monte Carlo defines the proper cuts to be applied to the data sample and evaluates the precision in the measurement of rock depth and bundle multiplicity. The events have been generated with the HEMAS-DPM (Battistoni, 1995) shower code and the detector response has been simulated with the GEANT-based GMACRO Monte Carlo.

For the following calculations we have used the last release V0.7-2 of HEMAS-DPM. The main changes with respect to the previous release are the implementation of the earth curvature, which performs correct calculations at large zenith angle, and the inclusion of the new Gran Sasso map, which has been extended to  $\theta > 60^\circ$ . For the muon propagation in the rock we used the code PROPMU (Battistoni, 1997).

In the present version, the atmosphere profile above  $60^\circ$  is available only for Central Italy and for the average over the year. This is the profile adopted in the present calculation.

The last version of the HEMAS-DPM Monte Carlo includes a new Gran Sasso map which extends up to  $\theta = 94^\circ$ . However, the maximum zenith is limited by the description of the atmosphere profile up to  $89^\circ$ . It is important to note that in certain  $(\theta, \phi)$  directions the rock depth is not well known. In that case, the event was rejected.

The Monte Carlo HEMAS-DPM has been run with five mass groups combined to reproduce the MACRO Model (Ambrosio, 1997) obtained from the analysis of muon bundle multiplicities in MACRO. The HEMAS-DPM shower code provides, for each cosmic ray shower simulated, the muon bundle multiplicity and topology at underground level. The muons are folded into the MACRO detector using a variance reduction method developed in Battistoni, 1997.

One of the most delicate aspects of this analysis is the correct determination of the event multiplicity. For instance,

single muon events accompanied by electromagnetic showering are sometimes reconstructed as double muon events by the tracking program. Since the central planes of streamer tubes are horizontal, the event reconstruction is more difficult at large zenith angles. For this reason, the detector simulation includes an accurate treatment of the secondary particle production along the muon track, switching on all the main physical processes with low threshold values (muon bremsstrahlung, muon  $\delta$ -ray production,  $e^+e^-$  pair production etc.). Particles have been followed up to the following energy thresholds: 1 MeV for  $\gamma$  and  $e^+e^-$ ; 10 MeV for neutral and charged hadrons; 10 MeV for muons.

## 3 Data analysis

From the previously described Monte Carlo we defined the proper cut to select and analyse our data. We verified that these cuts do not erase any possible signal which could increase the ratio  $N_2/N_1$  at large depths. The main cuts are the following:

- 1) track directions (zenith and azimuth) reconstructed with different views must lie inside  $\Delta\theta < 1^\circ$  and  $\Delta\phi < 2^\circ$ ;
- 2) for double tracks, the relative projected distance in each view must be larger than 1m, to exclude the process of muon pair production by muons (Ambrosio, 1999);
- 3) for double tracks, the angular separation in each view must be  $< 3^\circ$ , to reject fake muon tracks generated by hadronic interactions in the rock surrounding the detector;
- 4) for each event, the number of hits used for the track reconstruction must be  $> 40\%$ , to exclude noisy events.

For the event sample 2 of Tab. 1, the event direction  $(\theta, \phi)$  is determined with the Horizontal Wires and Horizontal Strips measurement  $(\theta_{HH}, \phi_{HH})$ , using the average slopes in each view. For this sample, we reject events with tracks reconstructed using only the top (Attico) planes, because the direction and the multiplicity are often misreconstructed.

Events belonging to sample 3 have been analysed in a different way. These are events with no tracks reconstructed in Horizontal Wires and Horizontal Strips views. This means that there are less than 4 aligned hits in these views. It is possible to recover events with at least three aligned hits in the HW view, making a safe track fit. A large fraction of the

Rock bin ( $hg/cm^2$ )	$N_{det} = 1$		$N_{det} = 2$	
	$h < 7000$	$h > 7000$	$h < 7000$	$h > 7000$
$\sigma(\Delta\theta)$	$1.211^\circ$	$0.625^\circ$	$0.526^\circ$	$0.381^\circ$
$\sigma(\Delta\phi)$	$2.881^\circ$	$1.487^\circ$	$1.766^\circ$	$0.696^\circ$
$\sigma(\Delta h) \text{ } hg/cm^2$	254.0	308	41.7	178

**Table 2.** Monte Carlo study of the quality of event direction  $(\theta, \phi)$  and rock depth  $h(\theta, \phi)$  measurement for the whole data sample (Samples 1,2 and 3 together). We compare the Number of events and the RMS of the distributions of the differences between reconstructed and input variables. The results are reported separately for single and double muon events and for two different intervals of the true Rock depth  $h$ .

events have only two hits in the Horizontal Wire view, and cannot be analysed since these hits cannot be separated from the background hits.

As far as the event multiplicity determination is concerned, we found that the best measurement  $N_{det}$  of the “true” multiplicity  $N_{inp}$  is the biggest value among  $N_{HW}$  and  $N_{VW}$ . Via Monte Carlo, we estimated that the percentage of events with mis-reconstructed multiplicity is less than 3%, both for single and for double muon events.

In Table 2 we show the result of a Monte Carlo study of the quality of event direction  $(\theta, \phi)$  and rock depth  $h(\theta, \phi)$  measurement for the whole data sample (Samples 1,2 and 3 together). The results are reported separately for single and double muon events. We emphasise that the relative error in

rock reconstruction is always smaller than 10%.

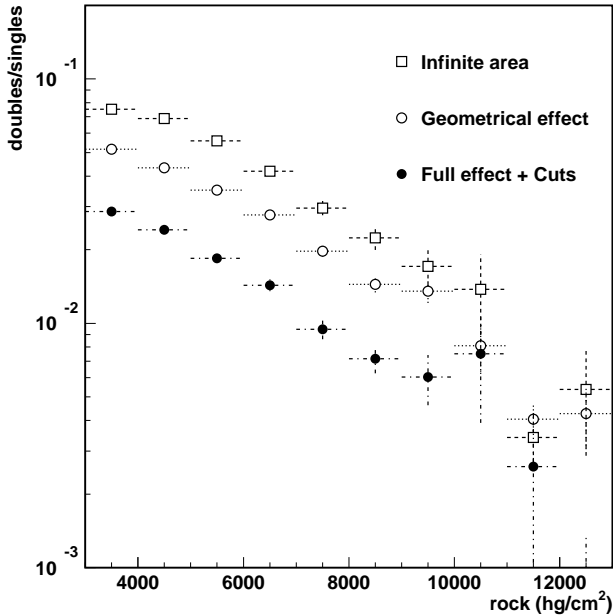
In Fig.1 we show the ratio of doubles to singles as a function of the rock depth obtained with Monte Carlo simulation. We compare the underground muons falling over an infinite area (i.e. neglecting all detector effects), those falling into a box with volume equal to detector fiducial volume (i.e. considering only geometrical detector effects) and those reconstructed by the complete detector simulation (i.e. with all detector effects and all cuts applied). Within statistical uncertainties, we find a monotonic decrease of all curves, as expected in a “standard physics” frame. We find also that there are no detector effects strongly dependent on rock depth.

In Fig.2 we show the number of detected singles ( $N_{det} = 1$ ) and doubles ( $N_{det} = 2$ ) as a function of rock depth. Their ratio  $N_2/N_1$  is plotted in Fig.3. Our results are in agreement with the expectation of a monotonic decrease of  $N_2/N_1$  down to  $h \sim 10,000 \text{ } hg/cm^2$ . Above this value, the insufficient statistics does not allow to state a firm conclusion on a possible increase of  $N_2/N_1$ .

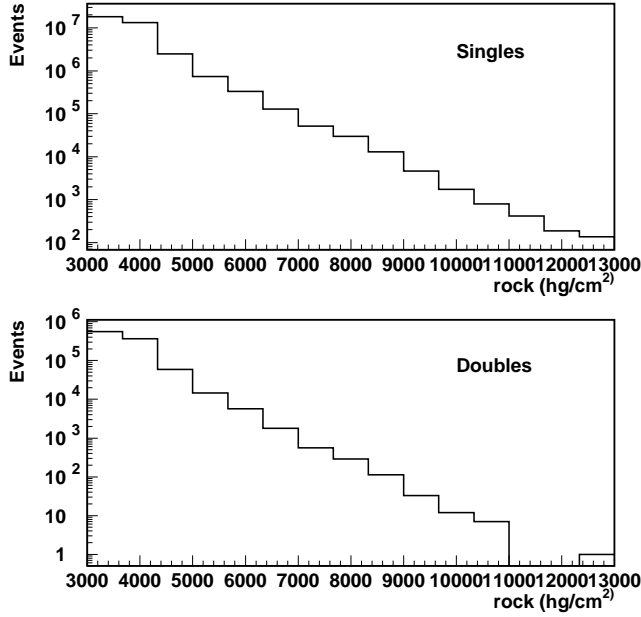
We remark that the Monte Carlo prediction is above experimental data for rock  $< 7,700 \text{ } hg/cm^2$ . However, the difference is small (less than 18%) and compatible with uncertainties on the primary cosmic ray flux and composition. Moreover, we stress that the MACRO composition model has been obtained from MACRO data, using a different interaction model. The calculation with the DPMJET model provides about 8% more single muon events and about 30% more doubles, thus a larger ratio  $N_2/N_1$  averaged over all rock depths. Finally, in the same plot we superimpose the expectations obtained using pure  $P$  and  $Fe$  primaries: it is clear that the choice of the composition model cannot explain any increase of  $N_2/N_1$  ratio as a function of rock depth.

We stress the importance of the cut number 4 quoted above: without this cut, the  $N_2/N_1$  ratio exhibits a sharp increase around  $7000 \text{ } hg/cm^2$ . This is due to noisy events which are often mis-reconstructed by the tracking algorithms as multiple muon events at large zenith angles.

We have performed a visual scan of all double muons (47 events) corresponding to the last 4 rock bins in the figure. Three independent operators scanned the events and classified each event of the sample as: single, double,  $N_\mu > 2$  or anything else (electronic noise, radioactive background or undetermined event). The result of this scan is that almost all the double muon events ( $\simeq 90\%$ ) have been correctly reconstructed. Only the rock bin  $h = 9,666 \div 10,333 \text{ } hg/cm^2$  requires a relevant correction obtained by increasing the sin-



**Fig. 1.** Ratio of doubles to singles as function of the rock depth obtained with Monte Carlo simulation. We compare the underground muons falling over an infinite area (i.e. neglecting all detector effects), those falling into a box with volume equal to detector fiducial volume (i.e. considering only geometrical detector effects) and those reconstructed by the complete detector simulation (i.e. with full detector effect).



**Fig. 2.** Number of singles ( $N_{det} = 1$ ) and doubles ( $N_{det} = 2$ ) as a function of the reconstructed rock depth.

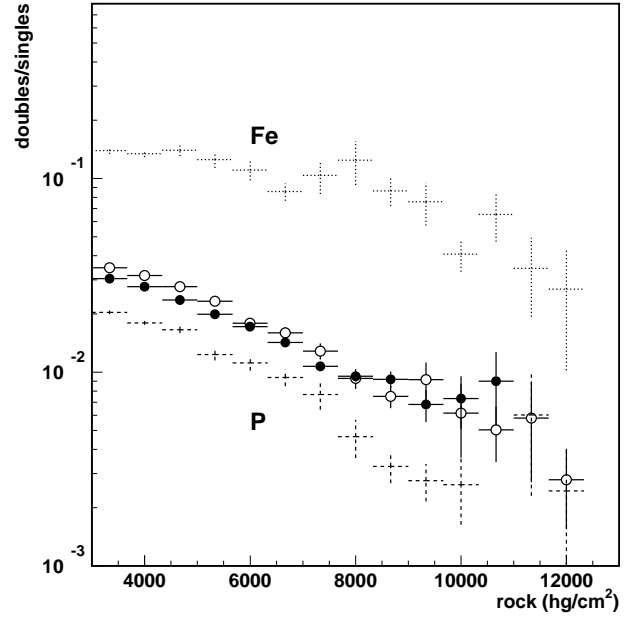
gle muon events by 16.7% and reducing the doubles to 66.7% of the original sample. The correction factor that should be applied on  $N_2/N_1$  is  $66.7/116.7 \sim 0.57$ , but this does not change qualitatively our conclusions. The point at the highest rock depth corresponds to only one double muon event and is confirmed by the three operators.

## 4 Conclusions

We presented the measurement of the ratio  $N_2/N_1$  of double muon events over single muon events, as a function of the rock depth, performed with the MACRO detector at Gran Sasso.

We verified with our HEMAS-DPM Monte Carlo that, if the processes of muon pair production by muons and of hadronic interactions in the rock surrounding the detector are rejected (with the appropriate cuts on relative distance and angular spread between muons), and the fraction of hits in-track over the total number of hits is larger than 40% (to reduce background and improve double muon identification), then the ratio  $N_2/N_1$  decreases as a function of the rock depth.

Our measurement is in agreement with the expectation of a monotonic decrease of  $N_2/N_1$  down to  $h \sim 10,000 \text{ hg/cm}^2$ . Above this value, the statistics are insufficient to allow a firm conclusion on a possible increase of  $N_2/N_1$ .



**Fig. 3.** Ratio of doubles ( $N_{det} = 2$ ) to singles ( $N_{det} = 1$ ) as a function of the reconstructed rock depth. Solid circles=DATA; Open circles=Monte Carlo with MACRO composition model. Monte Carlo predictions using pure Proton and Iron primaries are also shown.

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